Using Wave-Current Observation to Predict Bottom Sediment Processes on Muddy Beaches

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Grant Number: N00014-11-1-0272 (collaborative work with N00014-11-1-0269)

LONG-TERM GOALS

The proposed work investigates quantitatively the interaction between wave, currents and seabed sediments in shallow water over a bed characterized by heterogeneous, mud-dominated sediments. The long-term goal of is to develop an approach to characterize accurately the state of a muddy sea bed, based on minimal prior information about bed sediment, and remote observations of surface waves and currents.

OBJECTIVES

This work is a collaborative study between University of Florida (PI: Alex Sheremet; N00014-11-1-0269) and University of Delaware. The objective of the project is to investigate the possibility to predict bottom sediment processes using field data collected during the MURI Wave-Mud experiment. The observational data will be used to identify typical, *predictable scenarios* (sequences of states) of the evolution of bed rheology under energetic waves. In parallel, we propose to develop a fully physical, high-detail pilot model for wave-sediment interaction. The pilot model will have two components: a numerical model for small-scale bottom sediment transport Hsu et al., 2009, and a stochastic model for nonlinear wave propagation (Agnon and Sheremet, 1997; Sheremet et al., 2010). The data will be used to validate the model and propose simplifications for operational implementations. These goals are aligned with all three major ONR research thrust areas: nearshore, estuarine and riverine processes; remote sensing of the coastal environment; and sediment transport.

APPROACH

Laboratory and field observations show that soft muddy bottoms and near-bed fluid mud layers can dissipate as much as 80% of wave energy over a distance of just a few wave lengths (Gade, 1957; Jiang and Mehta, 1995; deWitt, 1995; Hill and Foda, 1999; Chan and Liu, 2009; Holland et al., 2009; and others). Many theoretical models of wave-mud interaction have been proposed, involving a range of rheologies and dissipation mechanisms. Mud has been described as a viscous Newtonian fluid (Dalrymple and Liu, 1978; Ng, 2000; deWitt, 1995); visco-elastic solid (Jiang and Mehta, 1995); visco-plastic Bingham material (Mei and Liu, 1987; Chan and Liu, 2009); or poro-elastic material (Yamamoto and Takahashi, 1985). Other processes, in addition to viscous dissipation in the mud layer, have been hypothesized to contribute to wave damping, such as nonlinear interactions between surface

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2011		**00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Using Wave-Current Observation to Predict Bottom Sediment Processes on Muddy Beaches**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,Civil and Environmental Engineering,Center for Applied Coastal Research,Newark,DE,19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

and interfacial waves at the water-mud separation surface (Jamali et al., 2003). While linear rheology (simpler, e.g., shear modulus or shear viscosity independent of strain rate amplitude) is typically preferred in models over complex of nonlinear models (Chou, 1989; Chou et al., 1993; Mei and Liu, 1987), field observations provided by the "Subbottom Field Experiment" (N00014-10-1-0363) and previous projects suggest that complex rheologies might be quite relevant for applications. A definite sequence of stages of bed transformation (see Section Figure 1) emerges from the analysis Sheremet et al., 2005; Jaramillo et al., 2008; Robillard, 2009; Sahin et al., submitted a,s. Under energetic waves, the stiff bed softens, liquefies, expands, and mixes with water. This mobilizes a surficial layer of sediment that is then rapidly resuspended by near-bed turbulence (a burst-like process), significantly increasing the suspended sediment concentration in the entire water column. In turn, increased SSC acts as a negative feedback that controls the further development of the process by dampening near-bed turbulence and suppressing mixing. As the storm wanes, decaying near-bed turbulence allows the suspended sediment to settle, leading to the formation of fluid-mud layers. Eventually, through dewatering and consolidation, the stiff bed state is reached again.

The proposed work is based on the following hypotheses:

1. Wave history drives the evolution of the wave/bed-sediment system.
2. Surface waves and the muddy seabed evolve as coupled systems. Wave-induced bottom stress and turbulence (that drive bed evolution) is balanced by mud-induced wave dissipation (that controls bed stress levels).
3. The evolution of the bed follows predictable cycles.

The wave-sediment system is driven by waves, but its evolution path is determined by the coupling between wave and sedimentary processes. Different wave histories might therefore result in different evolution paths for bed reworking. Because waves are the main driving factor, a coupled wave-sediment numerical model driven by wave evolution can be developed to forecast the state of bed sediment.

The concept of typical scenarios for bed-rheology evolution during storms provides the basis for investigating bed responses to wave activity. A pilot wave-mud interaction model is being built as a loosely coupled wave-mud interaction model based on two existing codes: the numerical model for bottom sediment transport *(Hsu et al., 2009)*, and the stochastic nonlinear shallow-water wave propagation (Agnon and Sheremet, 1997; Kaihatu et al., 2007; Sheremet et al., 2010). The ongoing work has three directions of research:

Data analysis: reconstruct the sequence of bed states in storms captured in the field observations and identify typical scenarios for evolution of bed rheology.

Model development: improve existing wave and sediment transport model and combine them into a coupled wave-sediment system.

Model validation: simulate the collection of storms, to investigate the limitations of the model, as well as to understand typical evolution patterns of bed rheology.

WORK COMPLETED

Field experiment and data analysis: This part of the research is solely carried out by University of Florida team lead by PI Sheremet. Please refer to the report of the UF component of the project

Model development: Both numerical components of the pilot numerical model – stochastic nonlinear wave propagation (Agnon and Sheremet, 1997), and small-scale sediment transport (Hsu et al., 2009), were implemented and a thoroughly tested on field observations collected during the 2008 and 2010 field experiments (e.g., Safak et al., 2010; Sheremet et al., 2010; Sahin et al., submitted). A typical bed evolution cycle has been identified and studied in detail (e.g., Sahin et al., submitted b, see next section). An analysis of bed reworking during all observed storms is ongoing.

When the fluid mud model was originally developed (Hsu et al. 2009), there was no available information on the mud rheological properties and an empirical closure used in Le Hir et al. (2001) was adopted. Consequently, the rheology closure used in Hsu et al. (2009) only allows qualitative understanding on the effect of rheology on fluid mud transport. Without detailed the information on mud rheology, it is not possible to rigorously validate the numerical model and to develop predictive capability. Recently, PI Hsu and his visiting scholar Mr. Wen-Yang Hsu (PhD student of National Cheng-Kung University, Taiwan) have further investigated this issue. As part of his PhD study, Mr. Wen-Yang Hsu has carried out a comprehensive series of laboratory experiments on wave propagation over muddy bottom where detailed rheological properties (viscosity and yield stress) are also measured via rheometer. Currently, we are able to utilize measured rheologial properties in the 2DV version of the numerical model of wave-mud interaction (Torres-Freyermuth and Hsu 2010) to simulate the flume experiments and demonstrate good agreement between the model-predicted and measured dissipation of wave amplitude. This research effort provides a true validation of the numerical models utilized in this study. The new formulation on rheological closure will be used in the numerical model to simulate field experiment.

RESULTS

The present study is a collaborative work that closely connects field experiment, data analysis, bottom fluid mud modeling and wave modeling. For more detailed description on field instrumentation and site description, the reader is referred to the report of the UF component of the project. Only critical field data that is relevant to sediment modeling effort discussed here are presented (see Figure 1).
Bed Evolution: Figure 1 shows the detailed bed evolution as recorded by PC-ADP backscatter intensity at platform P3. Under energetic waves, the stiff bed softens, liquefies, expands, and mixes with water. The mobilized surficial layer of sediment is then rapidly resuspended by near-bed turbulence (a burst-like process), significantly increasing the suspended sediment concentration in the entire water column. In turn, increased SSC-induced stratification acts as a negative feedback that controls the further development of the process by dampening nearbed turbulence and suppressing mixing (Safak et al., 2010; Sahin et al., submitted a). As the storm wanes, decaying near-bed turbulence allows the suspended sediment to settle, leading to the formation of fluid-mud layers (Safak et al., 2010; Sheremet et al., 2010). Eventually, through dewatering and consolidation, the stiff bed state is reached again.

Vertical profile of suspended sediment concentration: The new method proposed by Sahin et al. (submitted a) for estimating the entire vertical profile of the suspended sediment concentration based on the acoustic backscatter was used to reconstruct the evolution of the suspended sediment mass

(Figure 2b). Together with flow information, the observed vertical structure of suspended sediment concentration can be used to constrain the fine-scale sediment transport model of Hsu et al. (2009). In turn, the analysis of the model output provides essential information about quantities that are difficult to observe directly, such as the near-bed turbulent stress (Figure 2d). The numerical model suggests a threshold bed-stress value of 0.52-0.75 Pa for bed mobilization (Atchafalaya mud). This value is itself dependent of the wave activity history.

IMPACT/APPLICATIONS

The project represents a convergence of several directions of research (near-shore wave modeling, cohesive sediment transport, the development of operational forecasting tools for nearshore circulation and waves, increase use of remote sensed information, etc) and etc), and collaboration efforts circumscribed by the MURI-lead effort to understand wave-mud interaction.

The project is coordinated in collaboration with other MURI related projects. The scope and approach of the present research builds on the strong, ongoing collaboration between U. Florida and U. Texas and U. Delaware, illustrated by a number of papers in print and in preparation. The field work was coordinated with the MURI group of researchers, especially regarding observational data sharing (boundary layer and sediment characteristics, Traykovski, Kineke, Dalrymple), and other researchers that participated in the MURI-lead field experiment (Elgar, Raubenheimer, Allison). The work represents a natural continuation and expansion of the PIs ongoing research projects. The proposed work also builds on our previous collaborations on wave modeling with Kaihatu (Texas AM).

This research also benefits from, and enhances, parallel research (Sheremet) funded under NOPP to improve existing operational wave-forecasting systems (WaveWatch III, SWAN, etc) by developing and implementing numerical modules for wave-mud interaction and nonlinear waves physics.

The bottom boundary layer fluid mud modeling component of the proposed work also benefits from, and enhances parallel research (Hsu) funded by ONR to develop multi-dimensional, turbulence resolving model for fine sediment transport driven by waves and tidal currents.

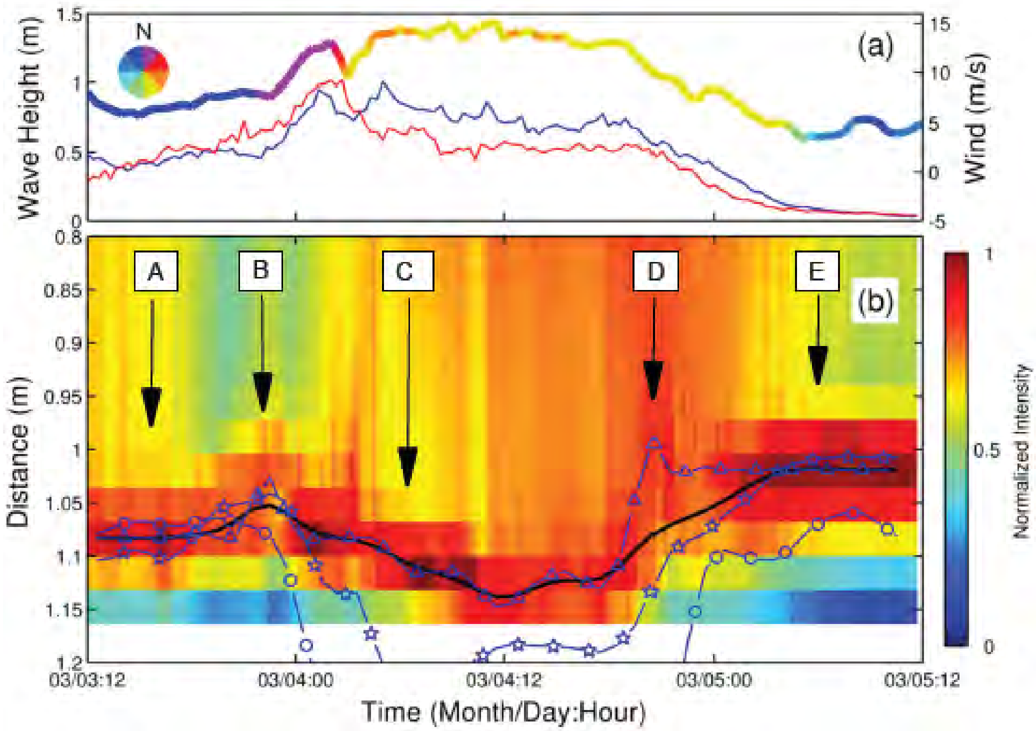

Figure 1: Analysis of PC-ADP backscatter showing a 20-30-cm thick surficial layer of the bed oscillating and sliding downslope during the storm. a) Significant wave height (blue: short waves, red: swell); and wind speed and direction (color code indicated the direction the wind blows toward). b) Normalized PC-ADP backscatter intensity. The lines represent the location of: maximum backscatter intensity (triangles); zero mean horizontal velocity (stars), and zero RMS horizontal velocity (circles). The continuous thick line is a smoothed estimate of the bed position. A surficial bed layer of approximately 20-30 cm oscillates with the waves and slides downslope. Arrows mark the hypothesized stages of bed evolution: (A) solid bed; (B) breaking of the bed matrix and water absorption (liquefaction/fluidization/expansion); (C) bed erosion; (D) settling and bed accretion; (E) formation of fluid mud. The process is followed by eventual dewatering/consolidation (not shown).

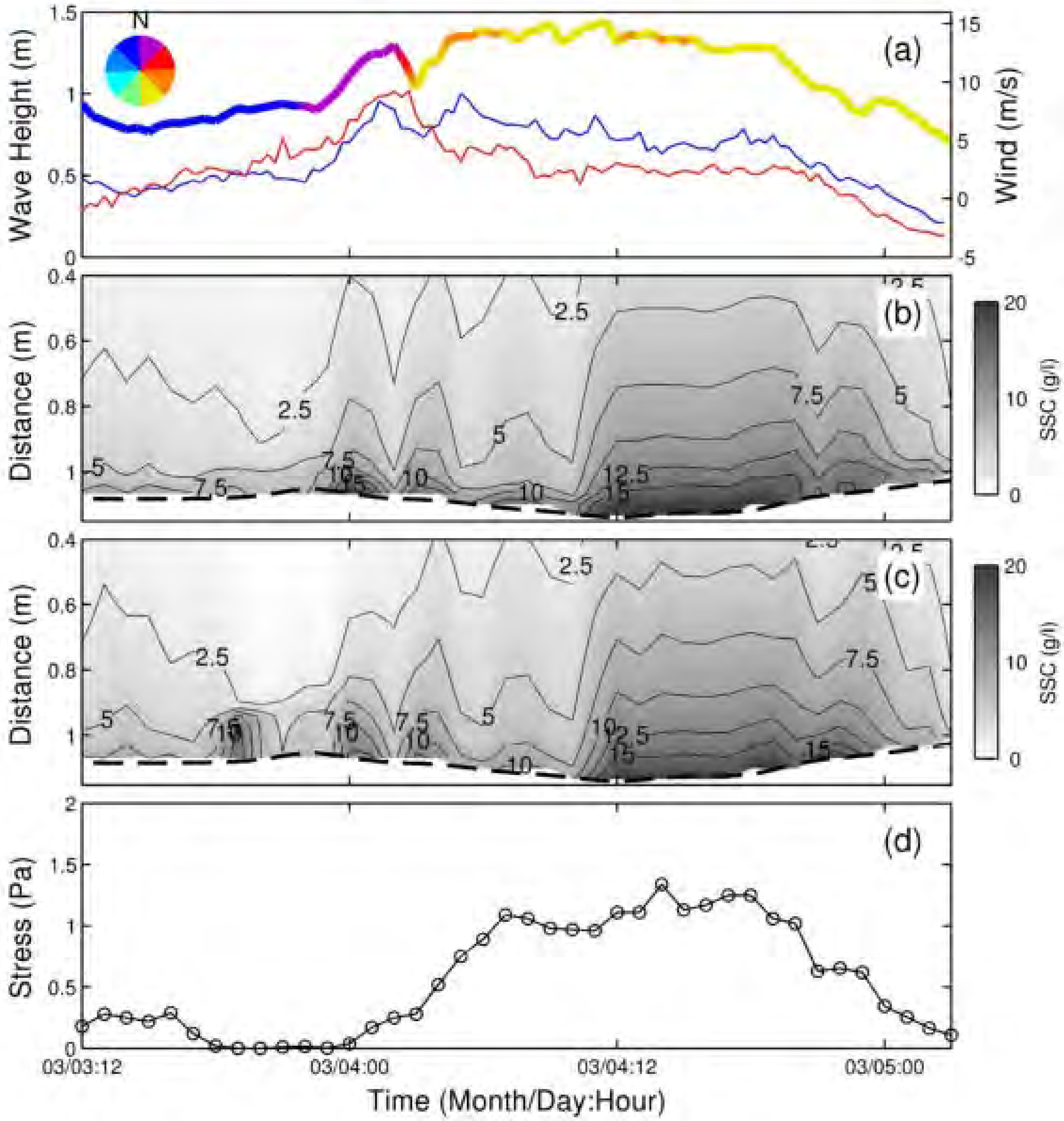

Figure 2: A reconstruction of the evolution of the vertical profile of the suspended sediment concentration during the storm of March 2008. a) estimates based on inverting the PC-ADP backscatter intensity (Sahin et al., submitted a), and numerical siumulations using the model of Hsu et al. (2009) of b) suspended sediment concentration profile, and c) bottom shear stress.

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